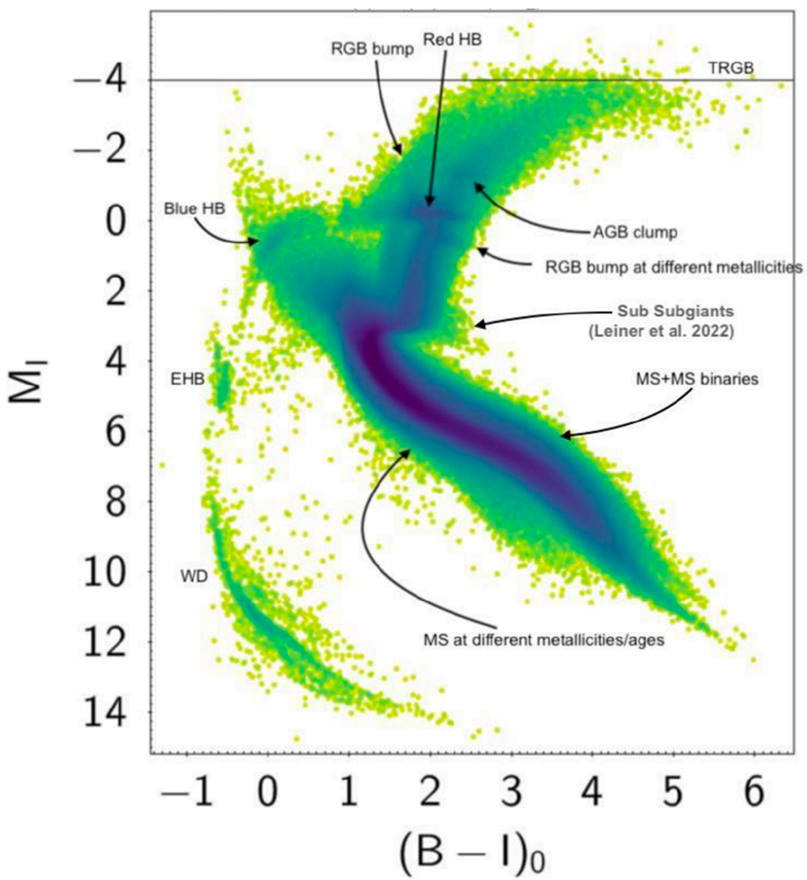
The Galaxy in your preferred colour: synthetic photometry from Gaia XP spectra

M. Bellazzini (INAF – OAS Bologna)



- Synthetic photometry, a natural by-product of Externally Calibrated (EC) BP/RP (XP) spectra
- Performances, limitations, perspectives for future DRs
- Examples of possible applications and value added products

It's a Gaia DPAC CU5 product Photometry

P. Montegriffo[1,★], M. Bellazzini[1], F. De Angeli[2], R. Andrae[5], M. A. Barstow[10], D. Bossini[18], A. Bragaglia[1], P. W. Burgess[2], C. Cacciari[1], J. M. Carrasco[4], N. Chornay[2], L. Delchambre[17], D. W. Evans[2], M. Fouesneau[5], Y. Fremat[15], D. Garabato[16], C. Jordi[4], M. Manteiga[16], D. Massari[1], L. Palaversa[6], E. Pancino[3,7], M. Riello[2], D. Ruz-Mieres[2], N. Sanna[3], R. Santoveña Gomez[16], R. Sordo[13], A. Vallenari[13], and N. A. Walton[2]

Core Team

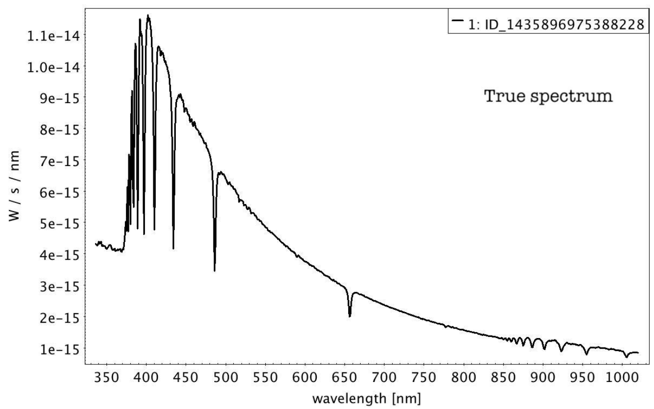
Gaia Collaboration 2022, A&A, https://doi.org/10.1051/0004-6361/202243709

Montegriffo et al. 2022 (https://doi.org/10.1051/0004-6361/202243880) illustrates the XP instrument model (IM)

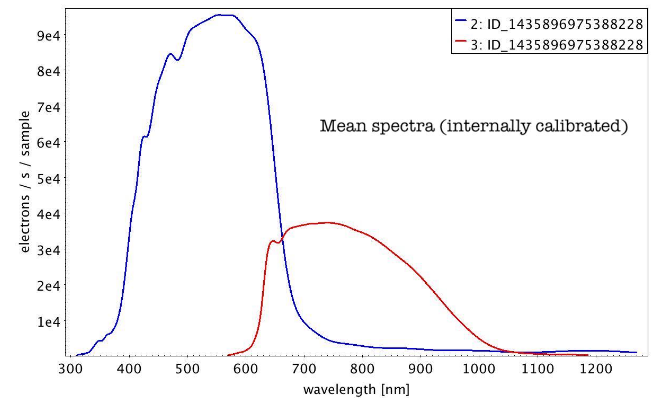
The IM is produced to allow forward modeling of spectra, allowing the comparison between models and observations in the plane of observations (mean XP spectra)

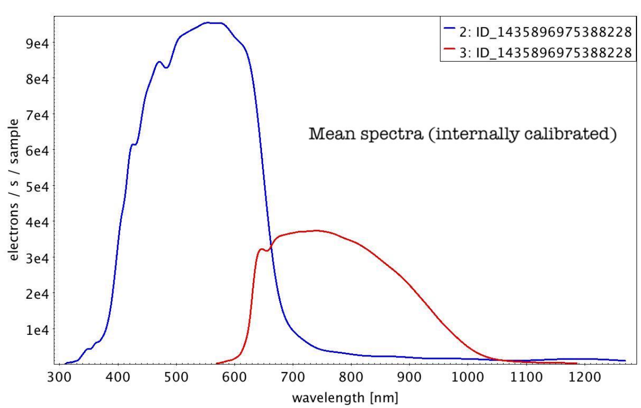
It can be used the other way around: convert observed spectra into EC spectra

- **Flux calibrated & Wavelength Calibrated**
- **(partially) Corrected for photon mixing inherent to slitless spectroscopy** ($25 \lesssim \lambda/\Delta\lambda \lesssim 80$)

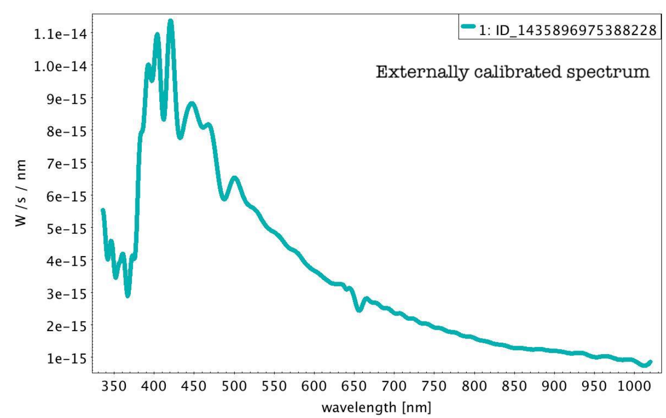


Observation by Gaia telescope + BP/RP spectrographs + internal calibration





Instrument model External calibration process



The key ingredient to derive the parameters of the IM is the grid of Gaia Spectro Photometric Standard Stars (SPSS), that is a set ground-based flux calibrated spectra purposedly assempled for this goal, thanks to the painstaking effort lead by **Elena Pancino** (see, e.g, Pancino et al. 2021)

Flux calibrated spectra can be used to get synthetic photometry

On June 13, 2022, with Gaia DR3 XP spectra for ≈220 Million sources (with G<17.65) were released for the first time making synthetic photometry from Gaia data possible.

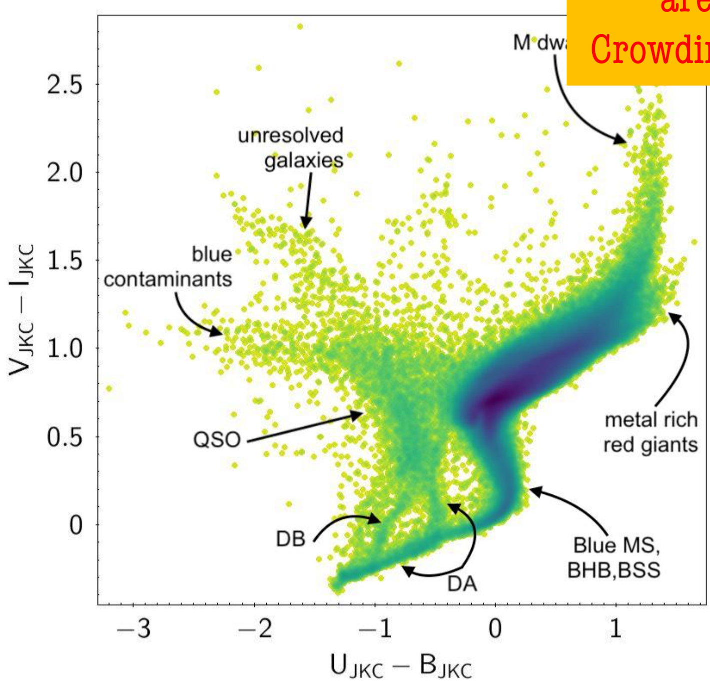
A Performance Verification Paper was devoted to illustrate this new product of the Gaia mission

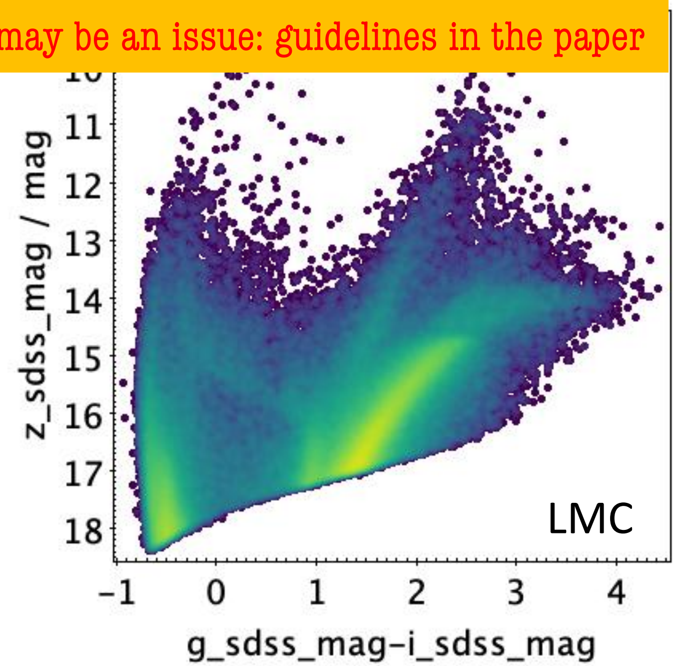
The value of Gaia XP synthetic photometry

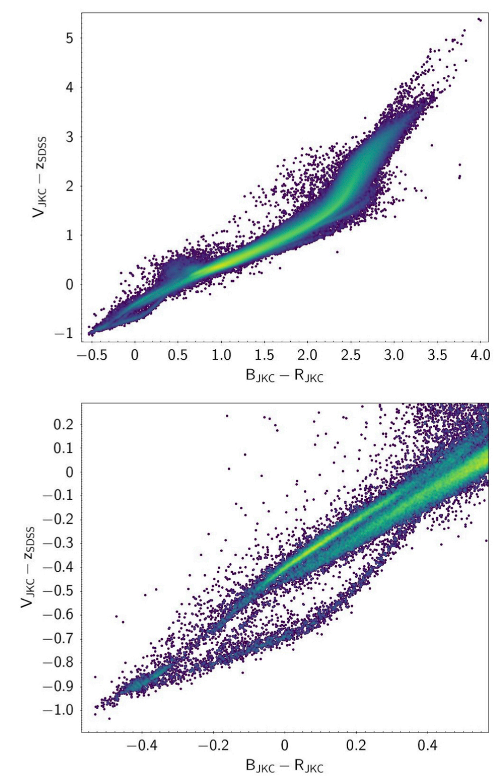
Extensive validation of XP spectra: spectral libraries include hundreds of spectra, spectral coverage not always matched. Modern photometric surveys (e.g, SDSS, PS1) provide <0.01 mag precision photometry for many millions of stars over huge portions of the sky

All sky, space-based, high precision photometry: to calibrate/validate photometric surveys. Scientific applications.

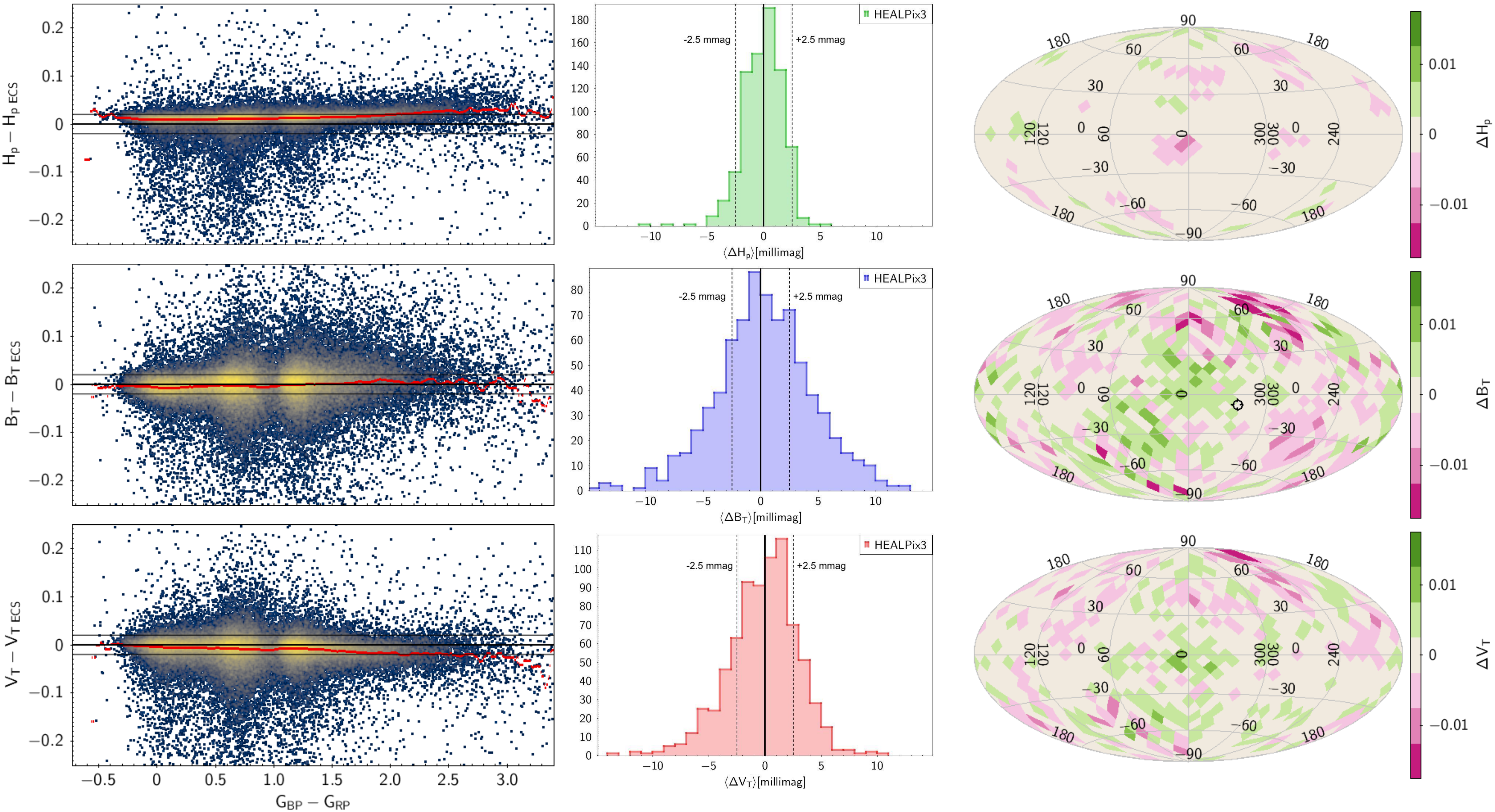
All the results I will show you
are for well-measured uncrowded sources
Crowding may be an issue: guidelines in the paper







All sky precision/accuracy: a glance to Hipparcos-Tycho



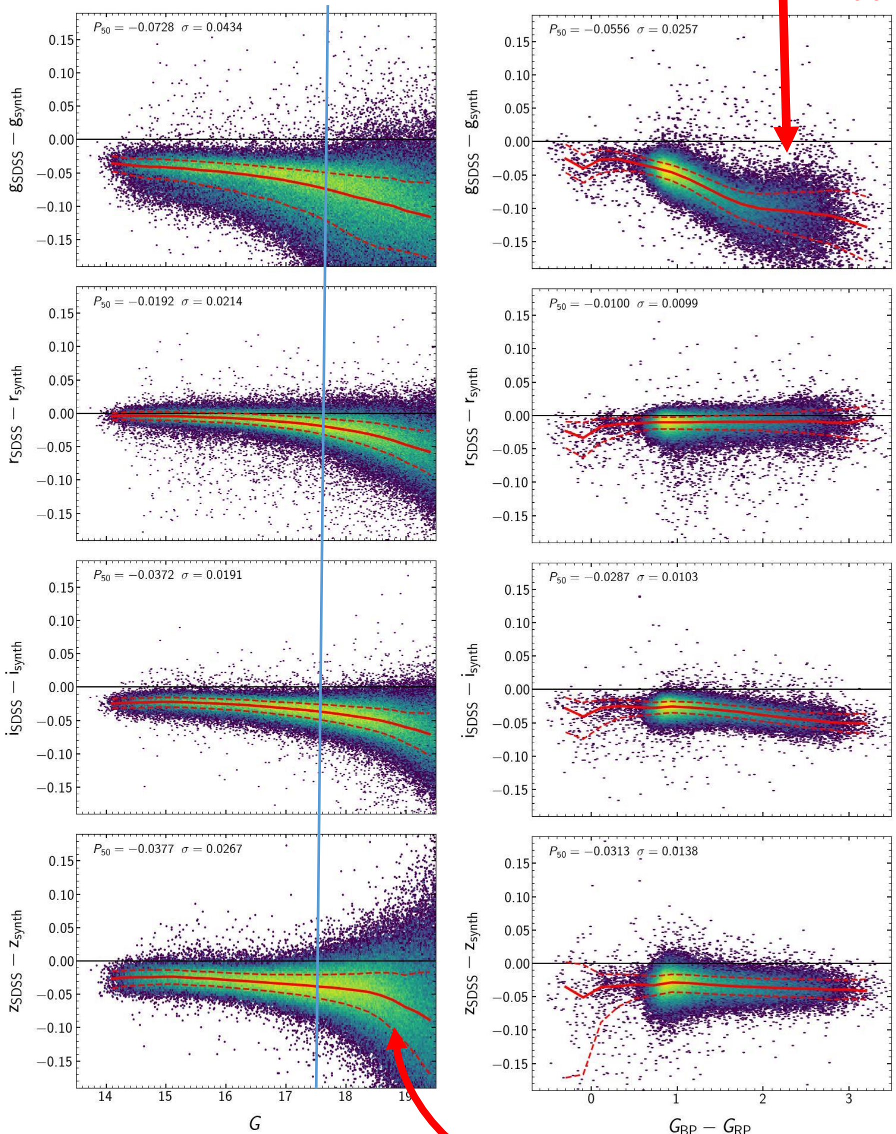
118218 stars with -0.608 <VT<12.058 from the Hipparcos core catalogue

Pretty good but not perfect. Examples

SDSS Stripe 82

Sp Ty dependent systematics for Blue and UV passbands

Landolt standard stars

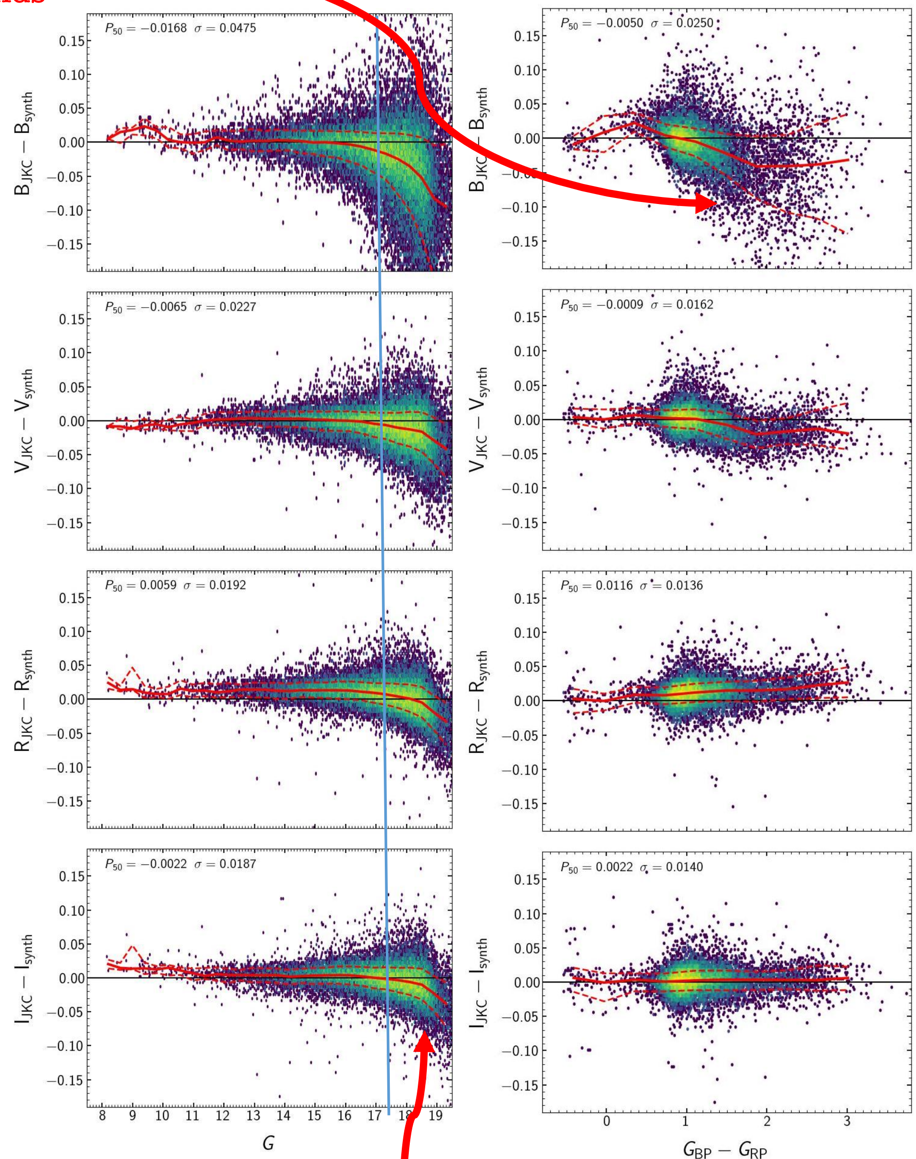


Small ZP differences (<0.05 mag)

Hockeystick effect: non-linearity arising at G≲15. Likely due to overestimate of the bkg in XP spectra

Note: we are limited To G<17.65; hockeystick amplitude tipically <0.01-0.02 mag in that range.

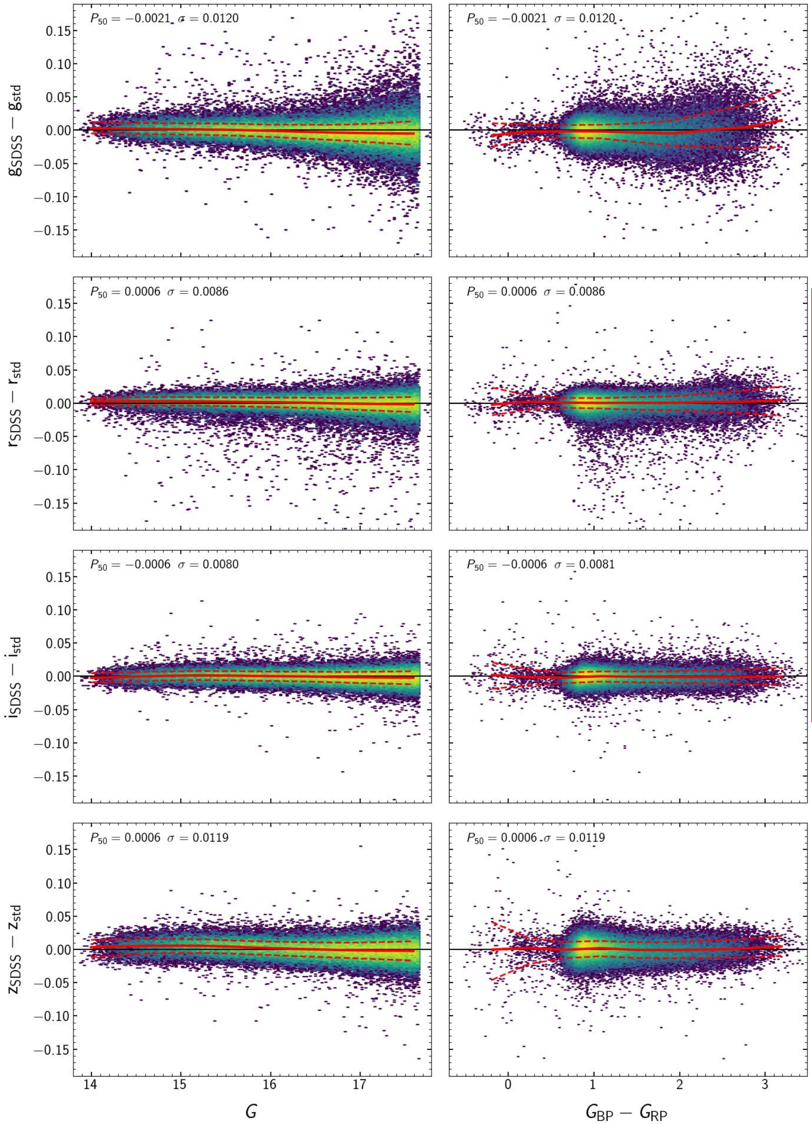
Small trends with colour, except for Passbands ranging λ≲550 nm



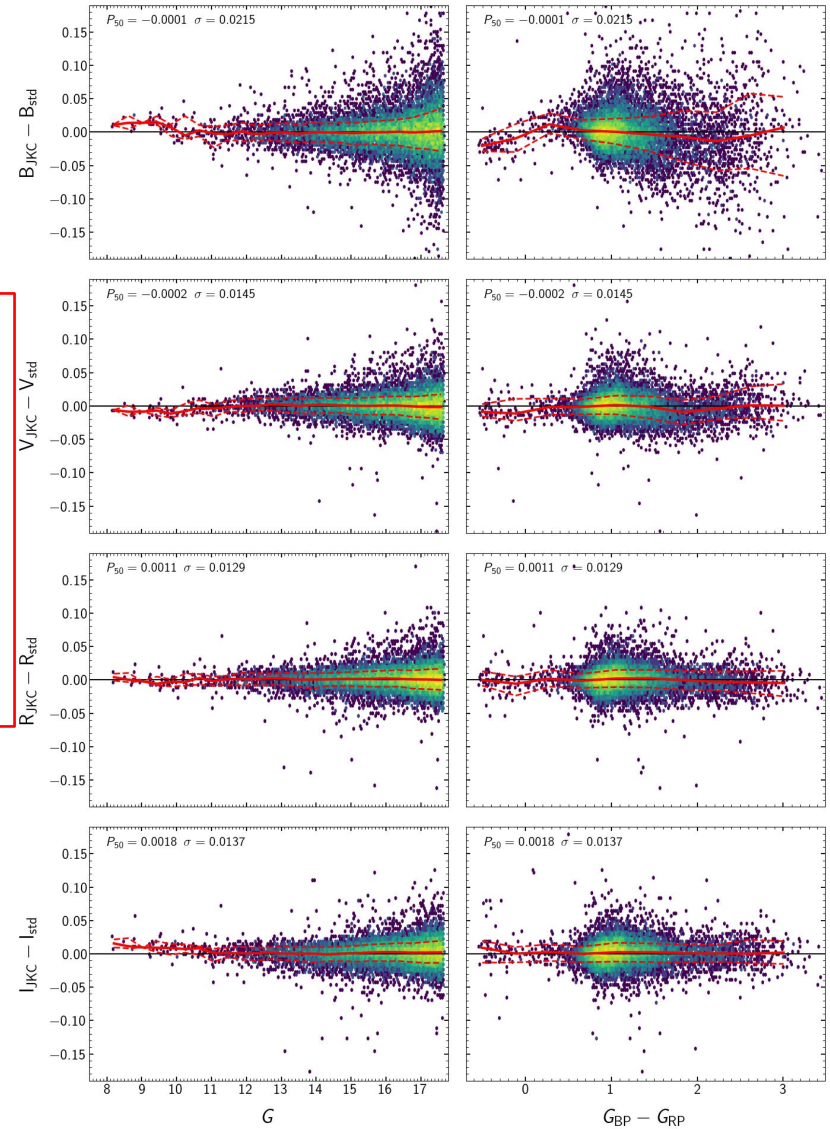
Hockey-stick effect (mainly due to background issues)

Pretty good but not perfect. How to deal with it: standardisation

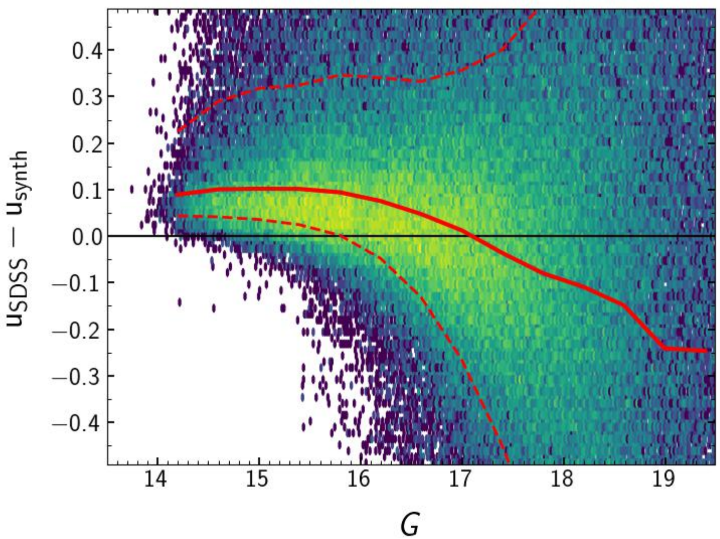
Use external photometry of selected sets of star to correct residual differences/trends (including hockeystick)

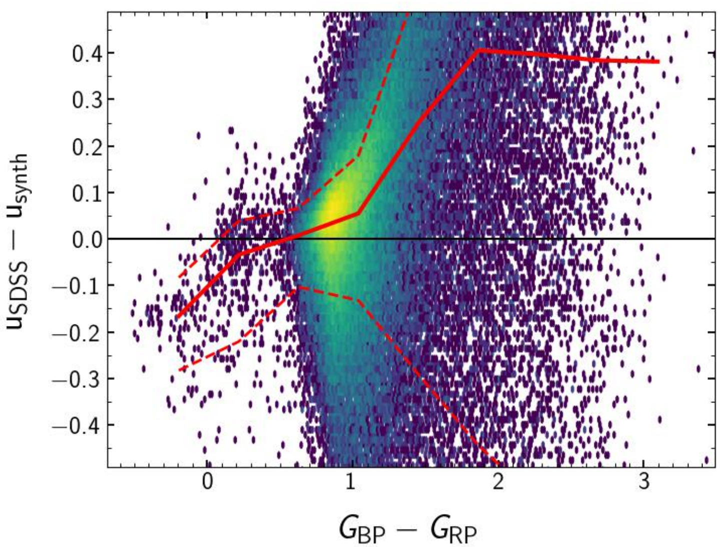


Wideband photometry in widely used systems is reproduced with millimag accuracy for passbands redder than B,g



Pretty good but not perfect: UV passband standardisation





Passbands below 400 nm are the most problematic:

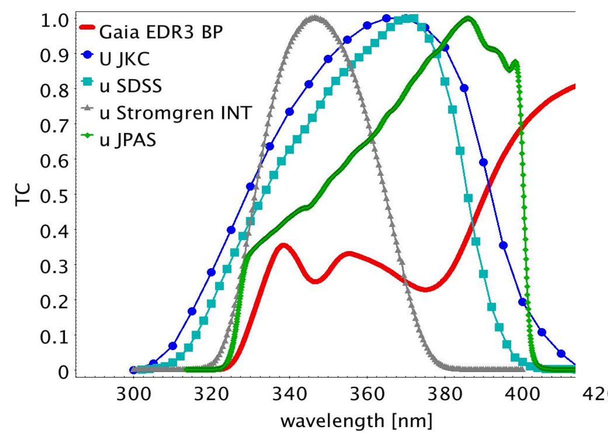
- Strongest systematics in EC XP spec that range

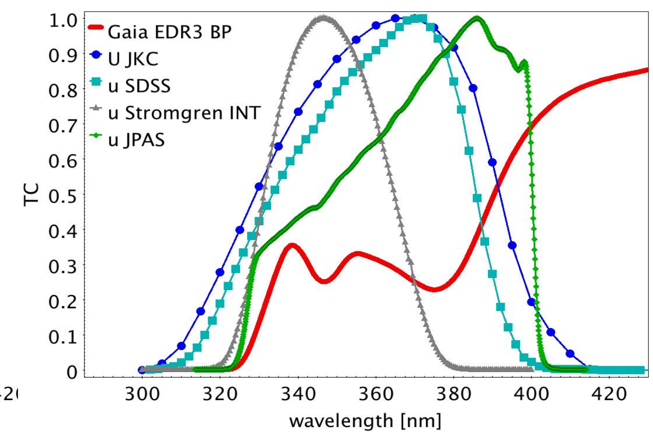
- Most widely used u passbands have a threshold to the blue of the BP cut-of

Passbands below 400 nm are the most problematic:

- Strongest systematics in EC XP spectra in that range

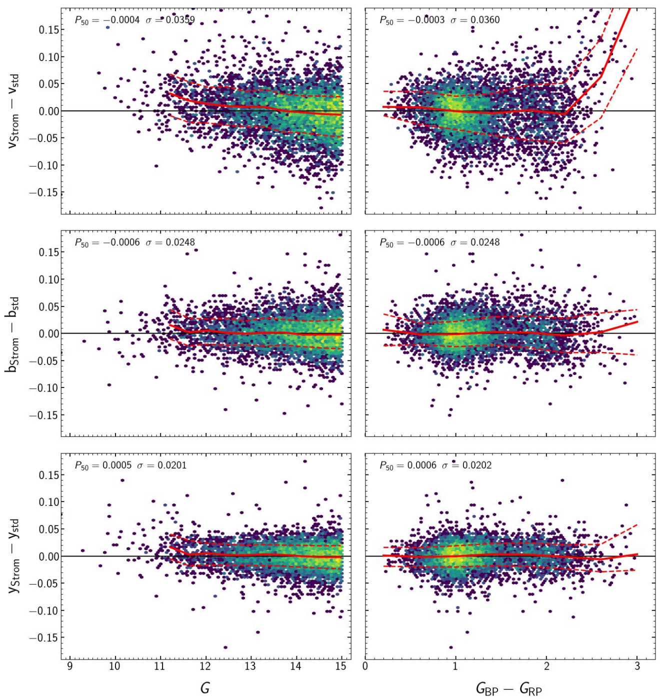
- Most widely used u passbands have a blue threshold to the blue of the BP cut-off

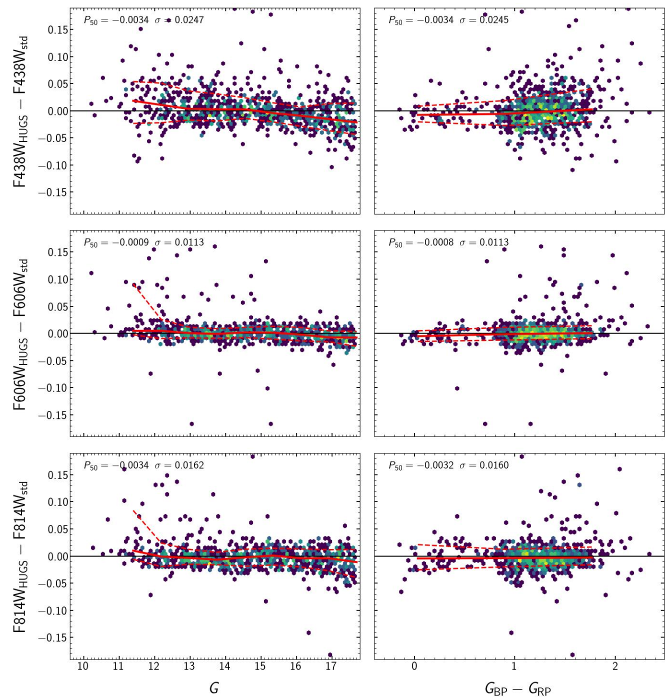


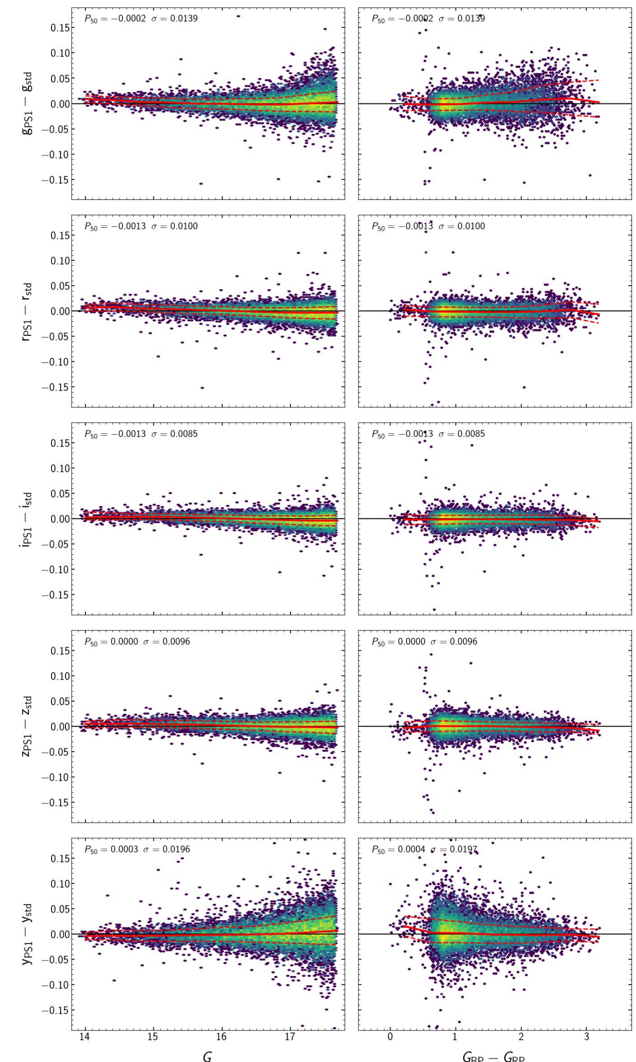


Standardised magnitudes: JKC UBVRI, SDSS ugriz, PS1 grizy, Stromgren vby, HST ACS/WFC F606W,F814W WFC3/UVIS F438W

Non-Standardised systems: IPHAS, J-Pas, J-Plus, Gaia-C1, HST-WFC3/UVIS and others



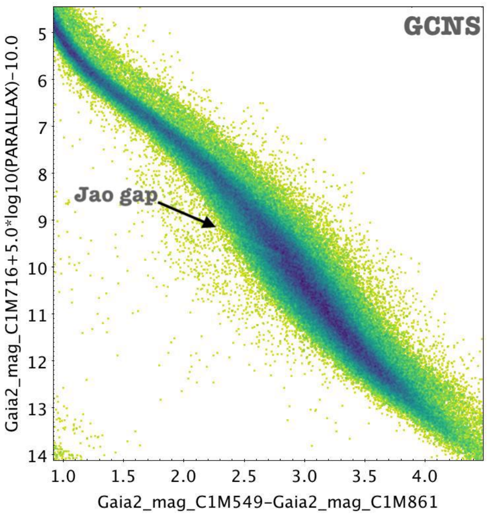


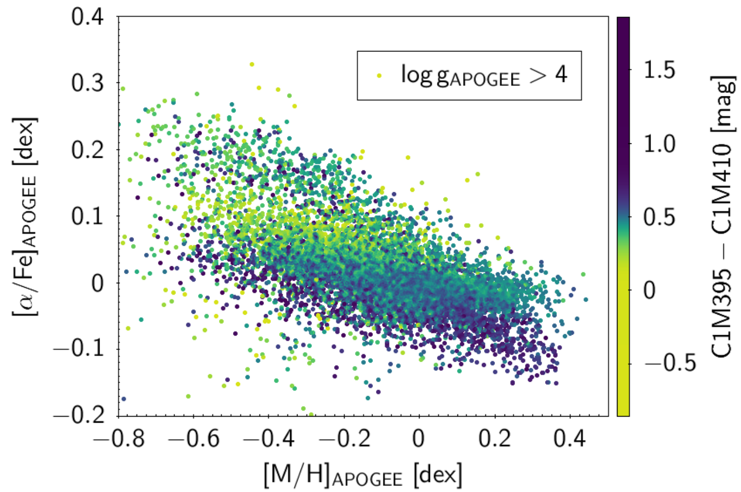


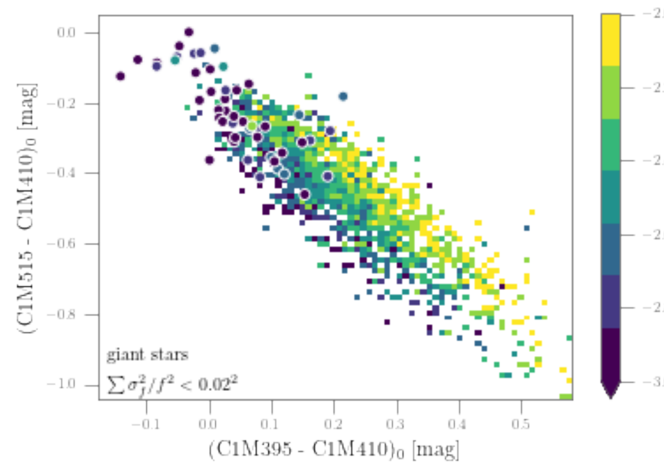
In the paper (59 pages) several standardised and non-standardised systems are discussed, **including narrow band photometry / line photometry** and its limitations. Also discussed: (a) uncertainties, (b) validation with additional independent external samples, (c) classification of sources with synthetic photometry using machine learning algorithms, (d) examples of science cases.

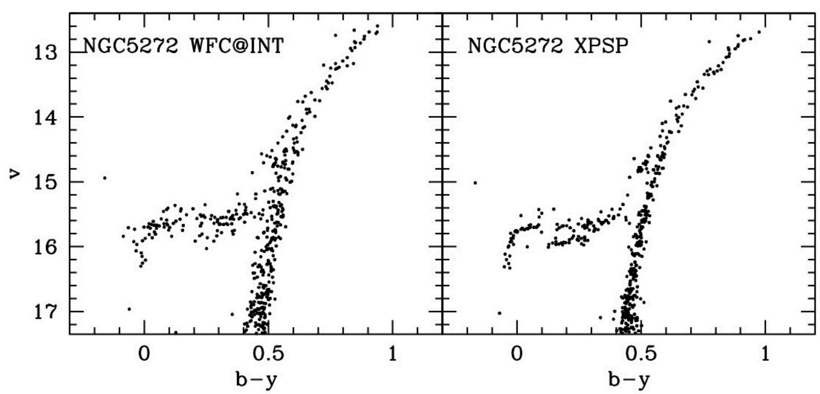
Examples of applications shown in the paper

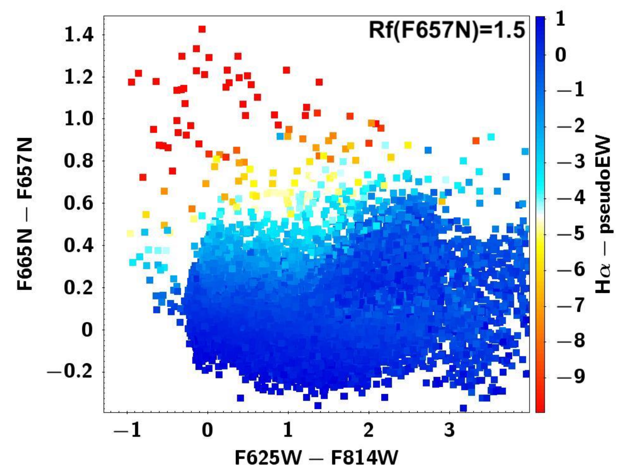
Jao gap: discovered with Gaia DR2, is interpreted as due to an instability occurring in the evolution of stars of mass M≈0.35 $M_\odot$











An example of application in the literature

The Poor Old Heart of the Milky Way

Hans-Walter Rix,[1] Vedant Chandra,[2] René Andrae,[1] Adrian M. Price-Whelan,[3] David H. Weinberg,[4] Charlie Conroy,[2] Morgan Fouesneau,[1] David W Hogg,[5,3,1] Francesca De Angeli,[6] Rohan P. Naidu,[7,*] Maosheng Xiang,[8] and Daniela Ruz-Mieres[6]

[1] Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
[2] Center for Astrophysics | Harvard & Smithsonian, 60 Garden St, Cambridge, MA 02138, USA
[3] Center for Computational Astrophysics, Flatiron Institute, 162 Fifth Avenue, New York, NY 10010, USA
[4] Department of Astronomy and Center for Cosmology and AstroParticle Physics, The Ohio State University, Columbus, OH 43210, USA
[5] Center for Cosmology and Particle Physics, Department of Physics, New York University, 726 Broadway, New York, NY 10003, USA
[6] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, UK
[7] MIT Kavli Institute for Astrophysics and Space Research, 77 Massachusetts Ave., Cambridge, MA 02139, USA
[8] National Astronomical Observatories of China, Chinese Academy of Sciences, Beijing, 100012, China

stro-ph.GA] 6 Sep 2022

ABSTRACT

Massive disk galaxies like our Milky Way should host an ancient, metal-poor, and centrally concentrated stellar population. This population reflects the star formation and enrichment in the few most massive progenitor components that coalesced at high redshift to form the *proto-Galaxy*. While metal-poor stars are known to reside in the inner few kiloparsecs of our Galaxy, current data do not yet provide a comprehensive picture of such a metal-poor "heart" of the Milky Way. We use information from Gaia DR3, especially the XP spectra, to construct a sample of 2 million bright ($G_{\rm BP} < 15.5$ mag) giant stars within 30° of the Galactic Center with robust [M/H] estimates, δ[M/H] $\lesssim 0.1$. For most sample members we can calculate orbits based on Gaia RVS velocities and astrometry. This sample reveals an

In practice, we follow the approach of Montegriffo, P. et al. (2022a) to calculate synthetic photometry from the XP spectra in a wide range of mostly narrowband filters, in particular those filters with established utility in identifying metal-poor stars: Strömgren filters (Strömgren 1966), JPAS+ filters (Marín-Franch et al. 2012) and Pristine H & K filters (Starkenburg et al. 2017). On this basis, we use XGBoost to train the prediction of [M/H] using the *entire* SDSS DR17 APOGEE of giants with $G_{\rm BP} < 15.5$ ($\sim 230{,}000$ stars). Details are given in the Appendix.

16 Rix et al.

Table 1. Test errors of [M/H] from XGBoost from 20-fold cross-validation using various numbers of XP coefficients. We quote the median absolute error and the root-mean-square error.

input features	median AE	RMSE
all 55 coefficients	0.061	0.145
first 40 coefficients only	0.059	0.138
first 30 coefficients only	0.060	0.137
first 20 coefficients only	0.062	0.139
first 10 coefficients only	0.066	0.144
XP colours only	0.078	0.154
all coefficients + XP colours	0.064	0.138
all coefficients + WISE	0.088	0.186
XP colours + WISE	0.067	0.136
all coefficients + XP colours + WISE	0.049	0.107

prove the [M/H] predictions for our sample (consisting of red giant stars by construction), we also restrict the training sample from SDSS DR17 sample to only giants, via $\log g < 3.5$.

This leaves us with a suitable choice of data features, for which we explored a number of options. Our starting point was the set of XP coefficients (De Angeli et al. 2022; Carrasco et al. 2021), which we normalized by the Gaia apparent G flux. In Table 1, we quote the test errors for using the different numbers of XP coefficients. The performance is overall very good but depend only weakly on how many coefficients we use. This suggests that also the high-order coefficients contain useful information, and, at least for this application and the APOGEE DR17 sample, a truncation of XP coefficients is neither required nor helpful in our case.

Given the results in Montegriffo, P. et al. (2022a), we then attempted to only use photometry synthesized from XP spectra using GaiaXPy[5] and combine this with ALL-WISE near-infrared photometry. Specifically, we syn-

$G - W_1$
$G_{\rm BP} - G_{\rm RP}$
$G_{\rm BP} - W_2$
$W_1 - W_2$
$\rm CaHK_{Pristine} - W_1$
$\rm CaHK_{Pristine} - v_{StromgrenStd}$
$\rm CaHK_{Pristine} - b_{StromgrenStd}$
$\rm CaHK_{Pristine} - y_{StromgrenStd}$
$\rm Jplus_g - Jplus_i$
$\rm Jplus_{0395} - CaHK_{Pristine}$
$\rm Jplus_{0515} - CaHK_{Pristine}$
$\rm Jplus_{0861} - CaHK_{Pristine}$
$G_{\rm RP} - \rm Jplus_i$
$v_{\rm StromgrenStd} - 2 \cdot b_{\rm StromgrenStd} + y_{\rm StromgrenStd}$
$\rm CaHK_{Pristine} - 2 \cdot Jplus_{0410} + Jplus_{0430}$

We emphasize that the $G_{\rm BP} - W_2$ color has the longest wavelength leverage and therefore is highly affected by extinction, whereas the $W_1 - W_2$ color is comparatively insensitive to extinction.

As is evident from Table 1, this final configuration has slightly worse performance than the best configuration. However, the median absolute errors are similar, that is, most sources get similar results. The only noteworthy difference is in the RMS error, suggesting that the final configuration may have a few more outliers. Still, the results are better than what we can achieve from coefficients alone.

A.2. *Further [M/H] Validation*

Figure 8 illustrates a cross-validation comparison of

While it is the entire spectrum that contains all the information on a given source provided by the XP spectrographs, a choice of well suited passbands may be the most effective choice to extract relevant info, integrating over the wavelength range containing the signal of interest and averaging out some of the noise affecting XP spectra. Plus > one century of experience in the use of photometry to study stars.

Main product: the Galaxy in your preferred colour with GaiaXPy

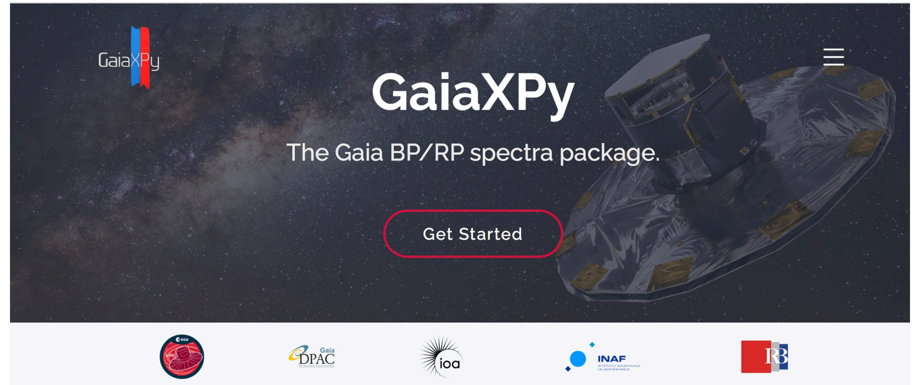
GaiaXPy

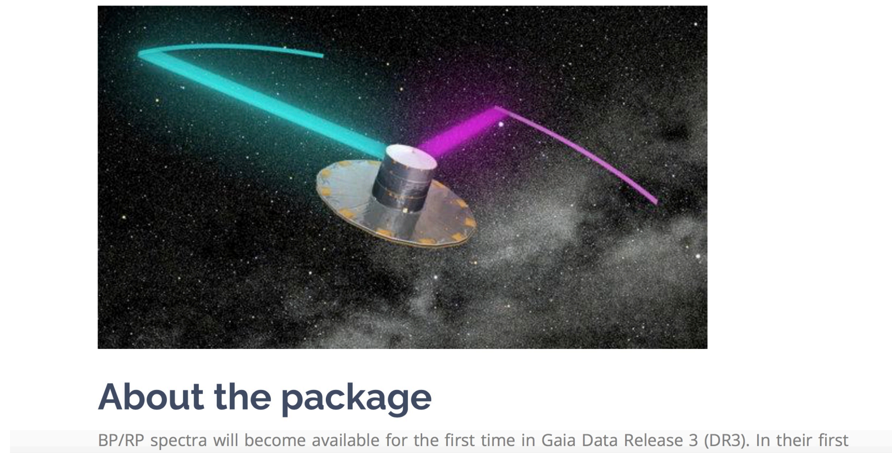
is the software tool allowing you to handle (and retieve) mean and EC XP spectra and

to get XP synthetic photometry of all the sources whose XP spectra has been made available in DR3 in any of the available photometric systems (standardised and/or non-standardised)

Many systems already available [see table]: JKC, SDSS, PS1, Gaia-2, Stromgren, J-PAS, J-Plus, DECam, Pristine, Skymapper, HST-WFC3/UVIS, JWST, Euclid, WFIRST, etc.

New systems can be added [see guidelines]





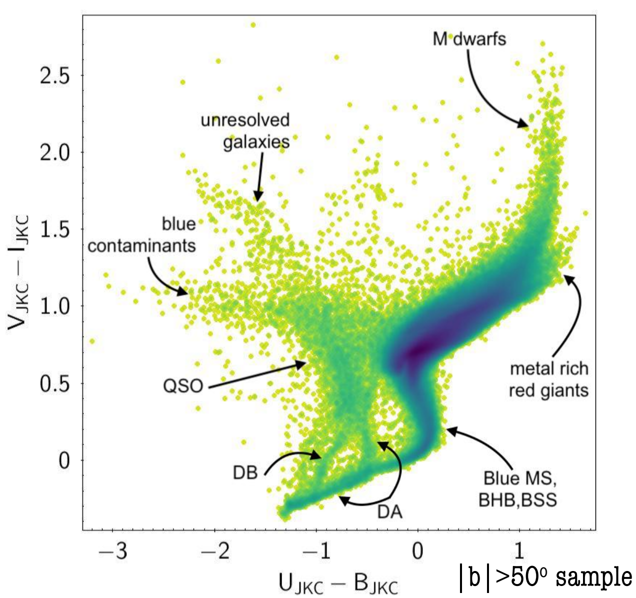
Also, e.g.: easy to have a look to the EC XP spectrum of a given source

Value added products

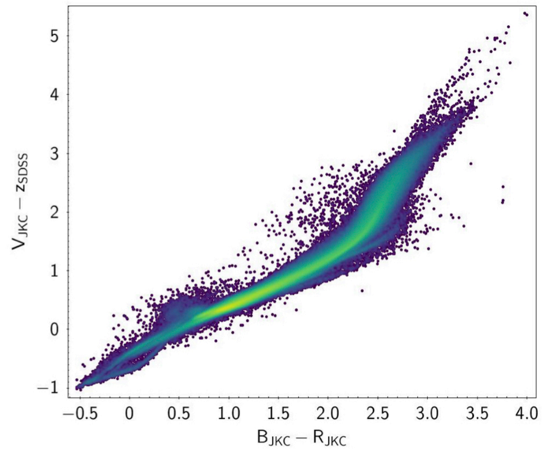
GSPC: standardised photometry (mag+fluxes+uncertainties) for 220 M sources in SDSS(ugriz), JKC(UBVRI), PS1(y), ACS/WFC(F606W,F814W). S/N>30 + quality flags

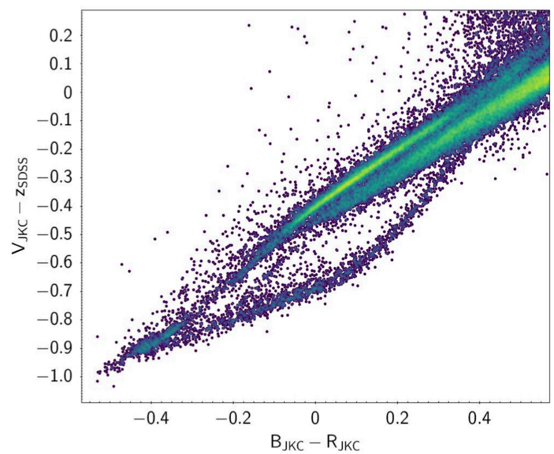
Query-able from Gaia archive:

`synthetic_photometry_gspc`



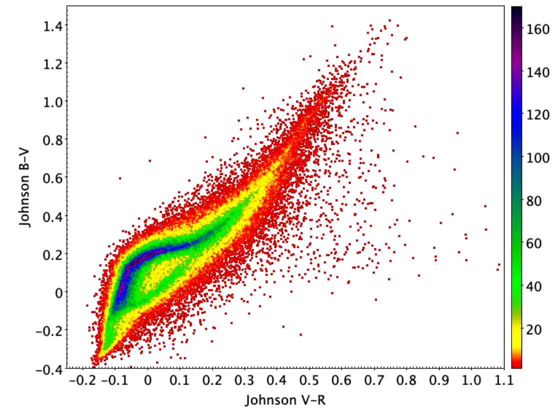
|b|>50° sample

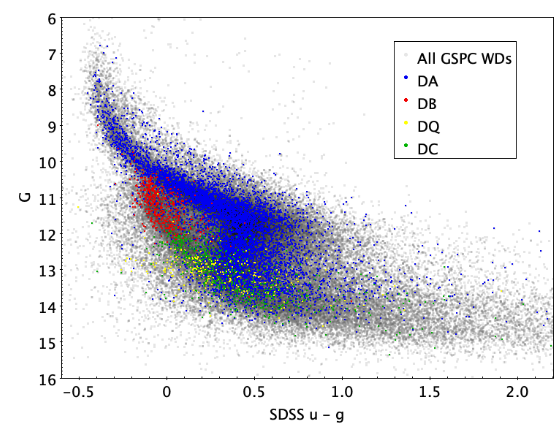




GSPC-WD: ≈100000 WD to G≈20 SDSS(ugriz), JKC(UBVRI),J-Plus with DA/non-DA classification from random forest on SP

Available on Zenodo





What we expect from future data releases

- XP spectra of fainter sources will be released: many more stars for which synthetic photometry can be obtained. Higher density / wider magnitude range for use as secondary standards. Removal of the scanning law imprint (selection in n_transit).

- Higher SNR at any magnitude ➔ improvement in precision (especially relevant for narrow-width passbands)

- Mitigation of systematics: improved background estimate and build up of the mean spectrum. Improved wavelength calibration, improved Response Curve, etc. ➔ better Instrument Model

- New SPSS release ➔ improvement in the number and quality of calibrators

- Experience from the use of XP spectra and XP synthetic photometry by the community

XP Synthetic Photometry is part of the Gaia heritage

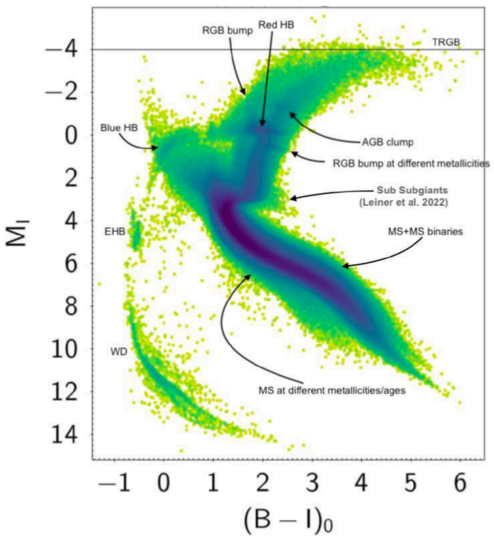
What I can do with XP synthetic photometry?

Calibrate / validate ground-based and space-based photometry: ideal for wide surveys
[e.g., we detect un-corrected trends in the most recent realisation of SDSS Stripe82 standards]

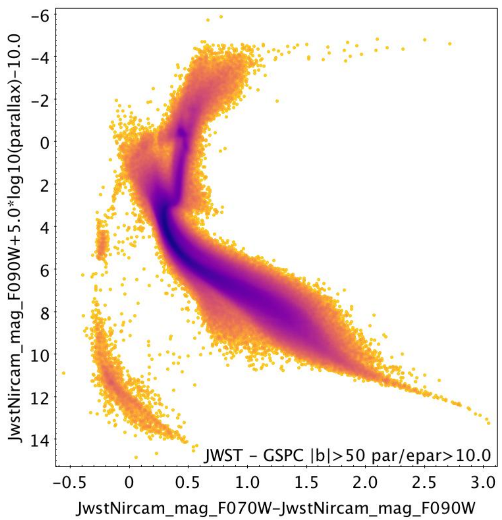
Plan future surveys by experimenting with real data and newly defined passbands

Use the set of colours and magnitudes that is best-suited for your specific science goal

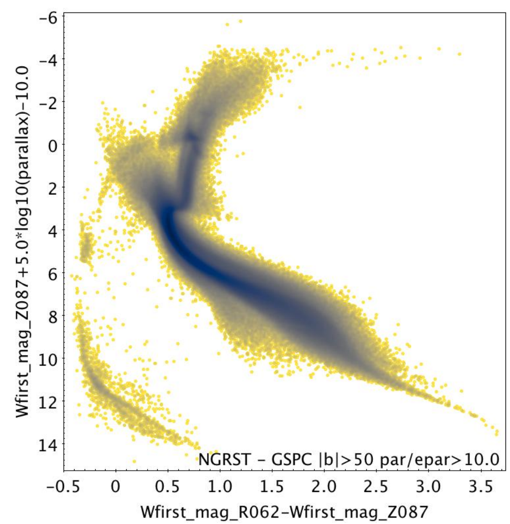
Calibrate diagnostics in the photometric systems of upcoming space missions / surveys



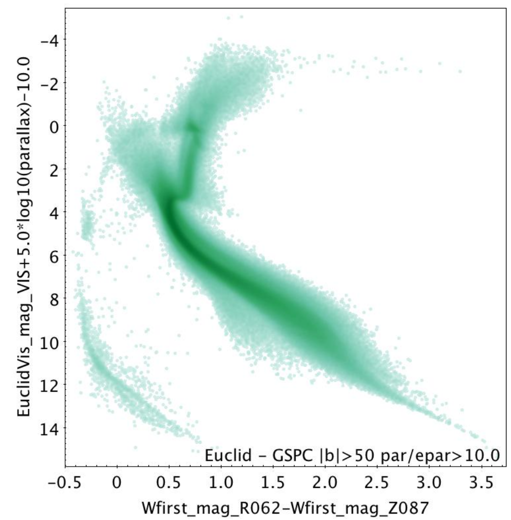
GSPC |b|>50° par/e_par>10
|C*|<0.05



JWST



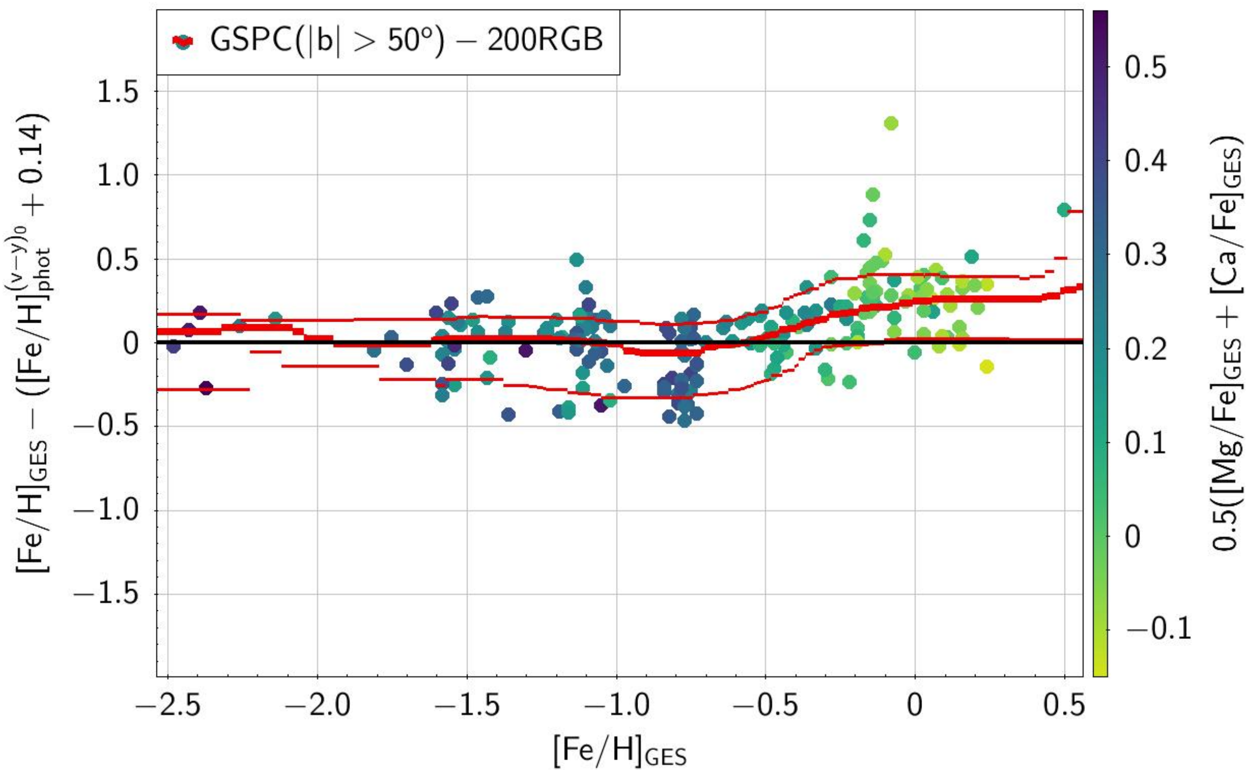
WFIRST
Nancy Grace Roman ST



Euclid VIS+
WFIRST

An example with the |b|>50° par/e_par>10 sample

Take standardised Stromgren photometry
Limit to stars with SNR(flux)>50 in v,b,y
Take E(B-V) from SFD98 maps (+ Schlafly et al. 2010 re-calibration)
Limit to stars with E(B-V)<0.2
Select RGB stars in the HR diagram
Use the [Fe/H]=f($m_{1,0}$, (v-y)0) calibration by Calamida et al. 2007

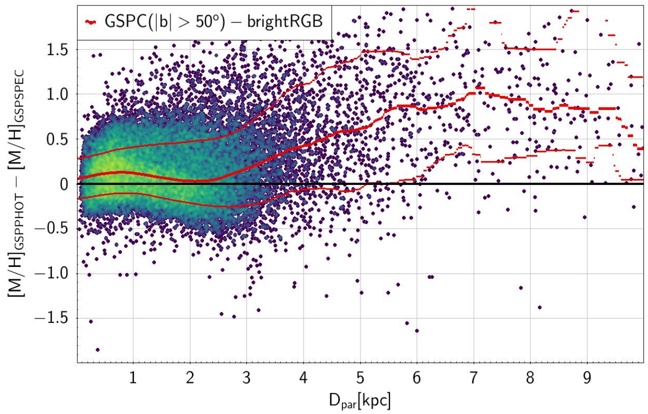


Comparison with spectroscopic [Fe/H] from Gaia ESO Survey – UVES sample

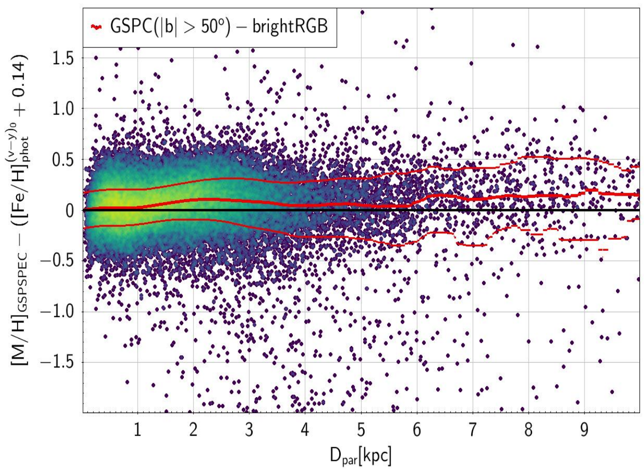
Tuning the calibration

Pretty good for [Fe/H]≲-0.5

An example with the |b|>50° par/e_par>10 sample: validation



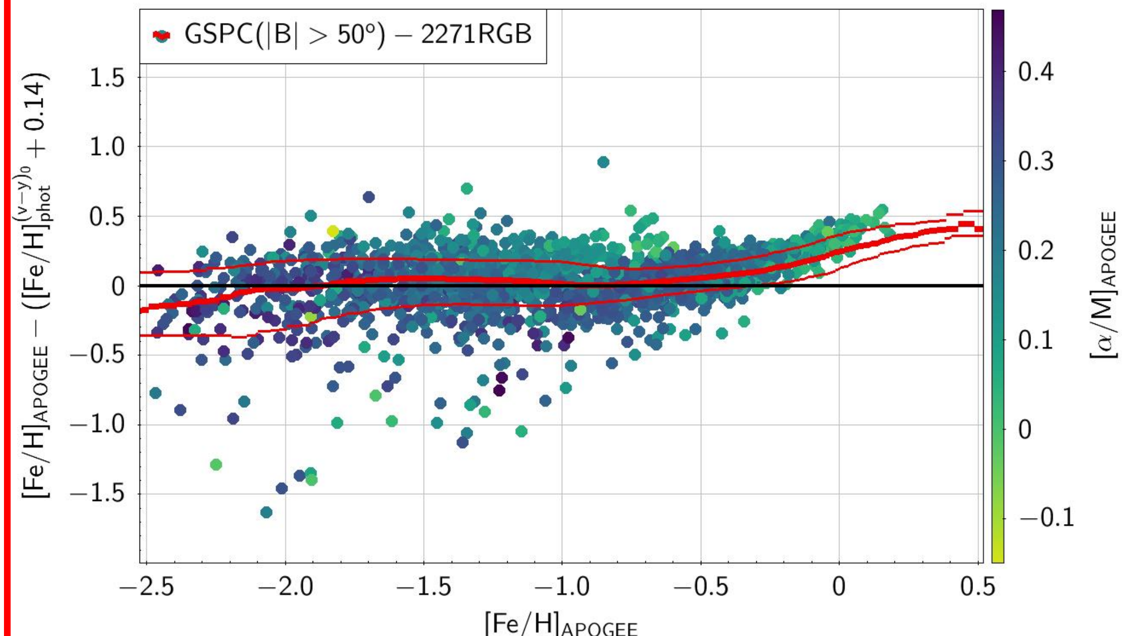
GSPSPEC
vs
GSPPHOT



Stromgren
vs
GSPSPEC

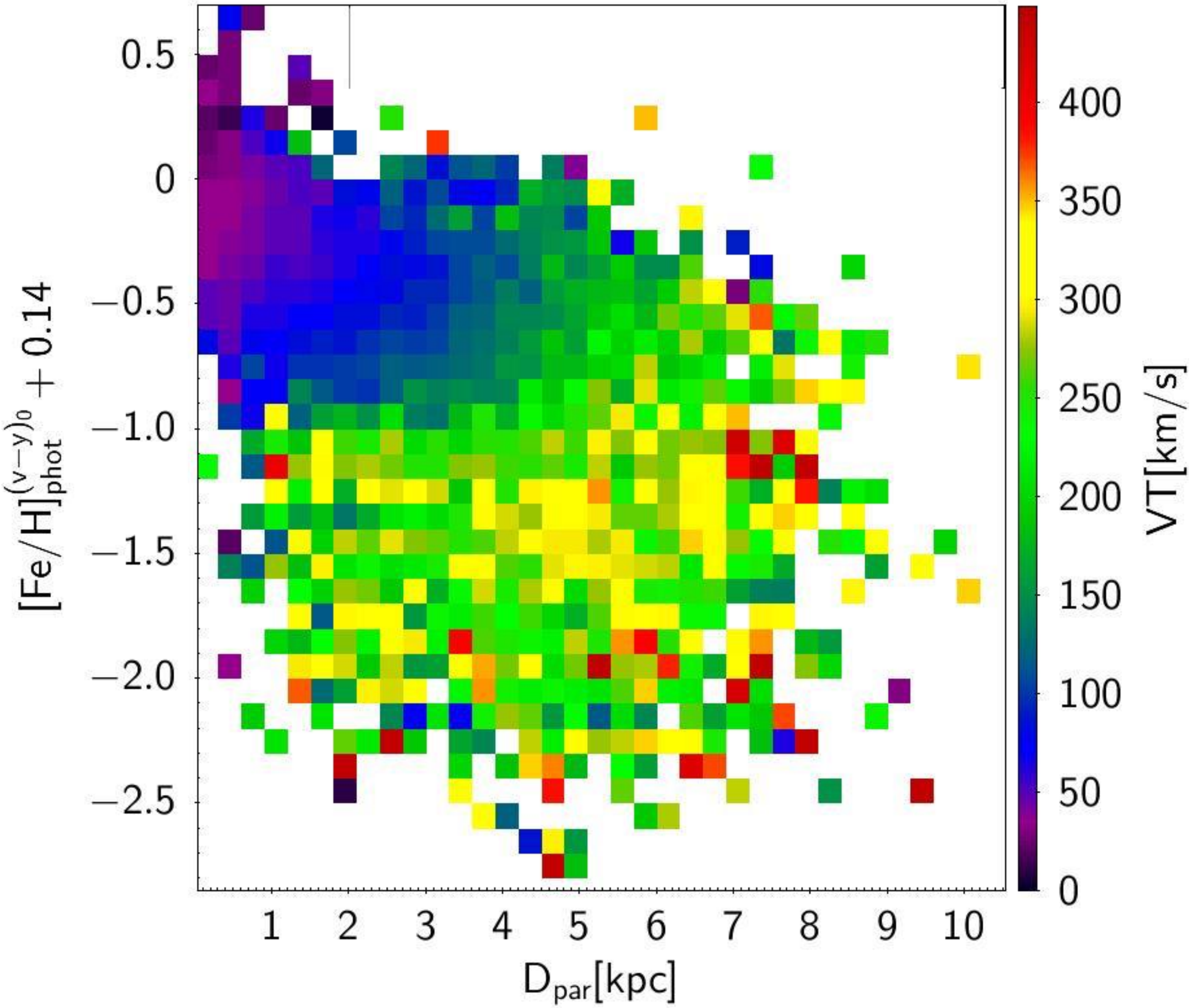
No selection on GSPSPEC
& GSPPHOT data:
Just a glance to the main trends

Spectroscopic [Fe/H] from APOGEE (SNR>70)



Pretty good!
GES re-calibration
accurately reproduce
APOGEE results!

An example with the |b|>50° par/e_par>10 sample: Chemo-kinematic properties

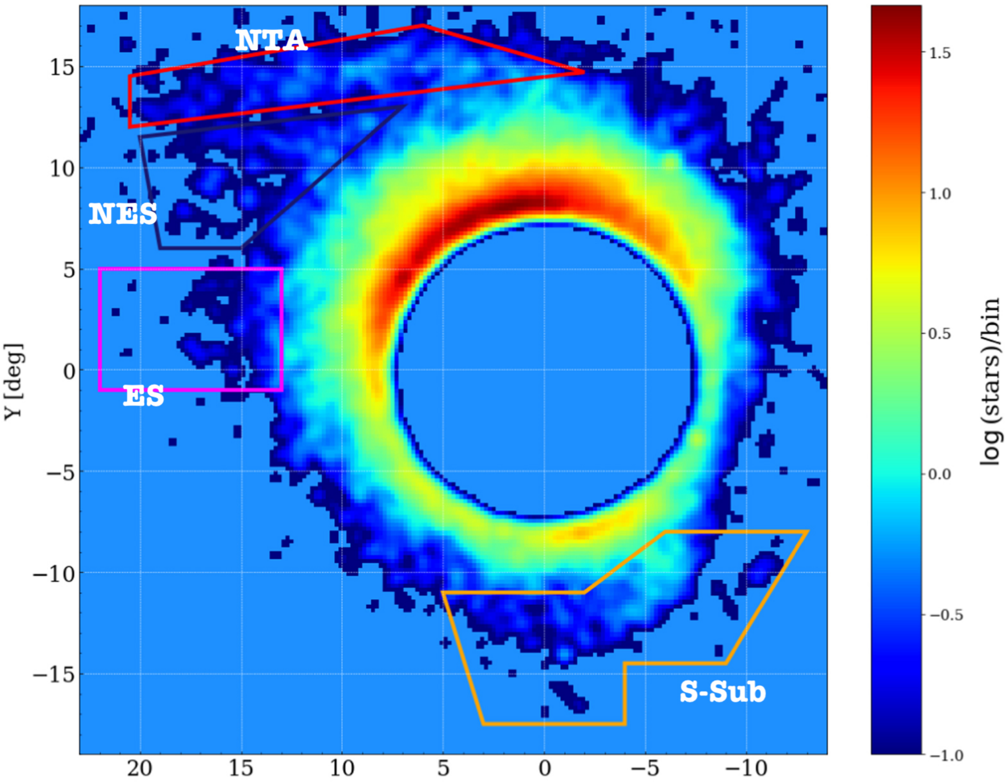


≈80 thousands RGB stars

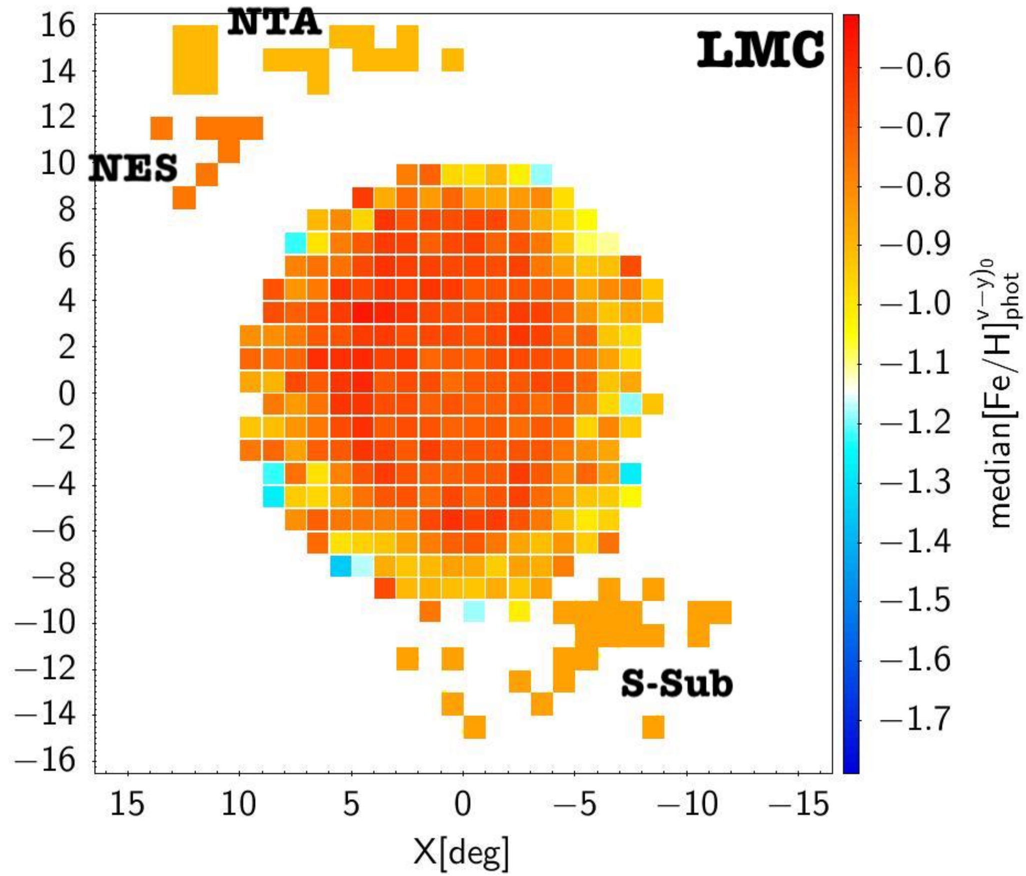
VT=(4.74/par)*sqrt(pmra²+pmdec²)

Meaningful picture of the part of the |b|>50° cone accessible with these data: thin disc, thick disc, halo

Median metallicity of substructures in the LMC from Gaia XP Stromgren photometry



Gatto et al. 2022, ApJ, 931, 19

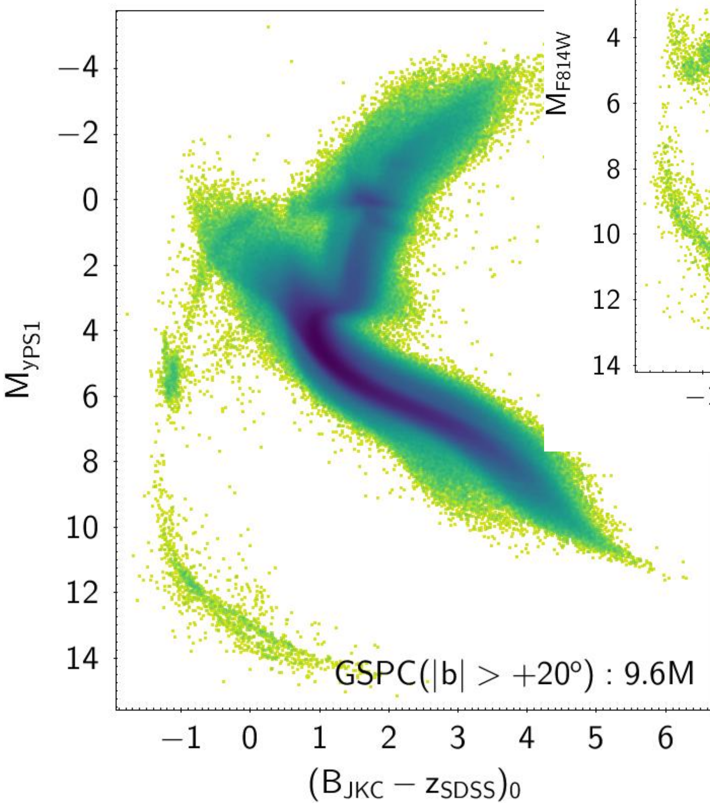


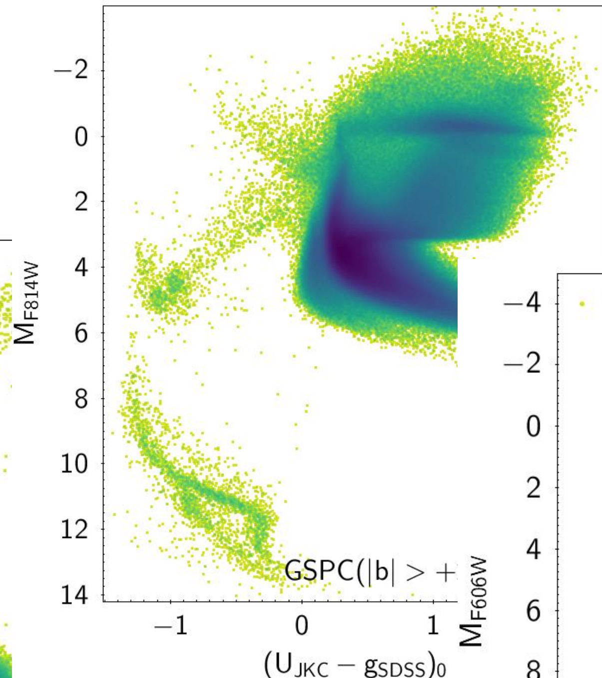
Confirming that substructures are mainly made of stars stripped from the LMC disc

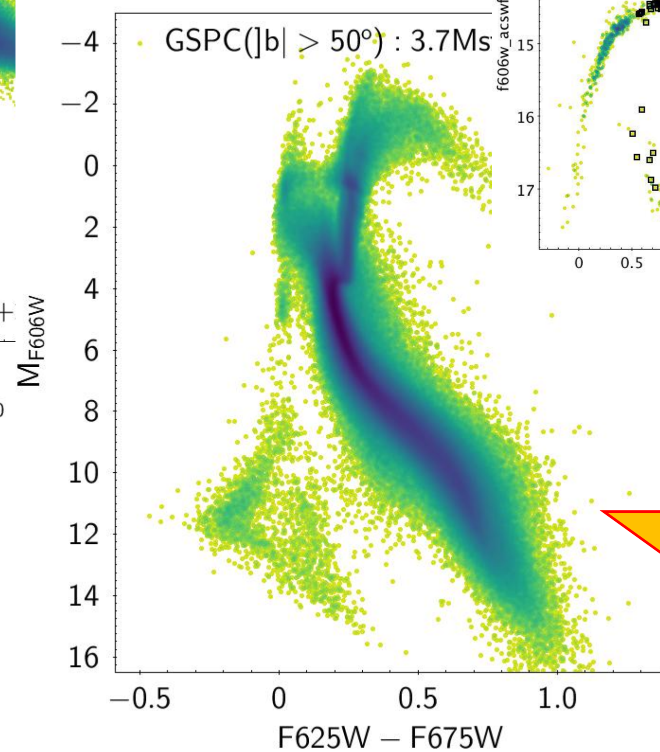
Gaia XP synthetic photometry: an asset for the present and the future

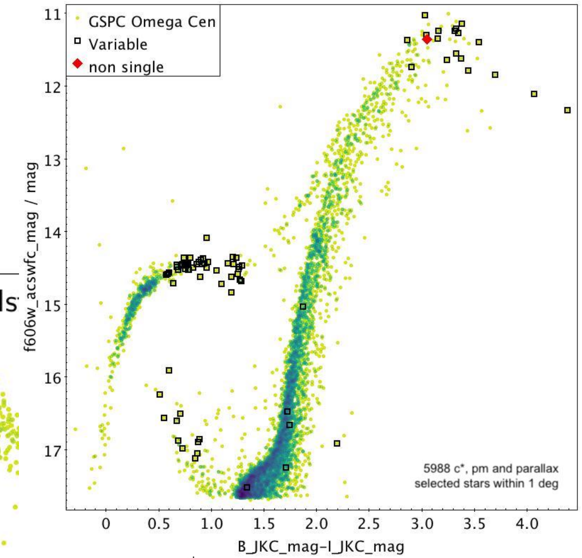
All Sky + Space-based is an unicum in the optical wavelength range (AllWISE in mid-IR)

Enjoy beautiful HR diagrams!









Thanks!